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Energy Procedia 75 (2015) 2415 – 2420

Energy Procedia

The 7th International Conference on Applied Energy – ICAE2015

Numerical study of the movement of fine particle in sound wave field

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Abstract

Inhalable particulate matter, especially PM2.5 is one of the main pollutants in China and it's harmful to both human health and atmosphere. Since the removal efficiency of traditional dust removal devices such as ESP for PM2.5 is very low, pretreatment becomes necessary before the dust gets into the dust remover. Acoustic agglomeration is one of the pretreatment technologies which uses sound wave with high intensity to make fine particles get agglomerate and grow up, and improves the efficiency of traditional dust removal devices for $PM_{2.5}$. In sound wave field, fine particles are carried by the medium which in this paper is air, and vibrate with different amplitude because of different particle sizes, thus relative movement appears and then particles have more chances to collide and get agglomerate. In this paper, the movement of particles with different sizes in travelling wave sound field and standing wave sound field were calculated, including the velocity, displacement, amplitude and so on. The situation that $Re<1$ was considered and Viscous force in Stokes region was chose as the main forces here. Studying the movement of fine particle in sound field with different conditions has great meaning in learning the mechanisms of acoustic agglomeration.

Peer-review under responsibility of Applied Energy Innovation Institute

Keywords: fine particle; sound wave field; numeraical study

1. Introduction

Inhalable particulate matter is one of the main pollutants in China and it's harmful to both human health and atmosphere. Particle with an aerodynamic diameter less than or equal to 2.5μm is called $PM_{2.5}$ or fine particle. It's the main cause of haze weather in China nowadays and causes a great concern [1]. What's more, $PM_{2.5}$ has very big specific surface area and it can absorb large amount of heavy metal, PAHs and some other toxic substances. And because of its tiny size it can get into human alveolus, which definitely hurts human body more than larger particle [2]. However, the removal efficiency for $PM_{2.5}$ of

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Peer-review under responsibility of Applied Energy Innovation Institute
doi:10.1016/j.egypro.2015.07.198

traditional dust removal devices such as ESP is quite low, so it becomes necessary to study the pretreatments of dust removal [3].

Acoustic agglomeration is a kind of pretreatment which uses sound waves with high intensity and a certain frequency to pretreat fine particles in the flue gas. The air in the sound field vibrates with the sprea of sound, and it carries particles with different sizes to vibrate with different amplitude. Relative movement between particles makes them agglomerate more frequently and grow up into bigger particles, and sequentially enhance the removal efficiency for fine particles of the follow-up dust removal devices.

There have been a lot of theoretical works [4-6] on acoustic agglomeration, but the conclusions are not totally consistent since the mechanisms are very complex. Orthokinetic interaction, which is widely recognized as the primary acoustic mechanism, is based on the entrainment of particles with different sizes caused by the intensive acoustic wave in poly-disperse aerosol [7]. Smaller particle is easier to be entrained. However, in mono-disperse aerosol, there was almost no orthokinetic interaction between these similar-size particles due to the absence of relative oscillatory motion and the Hydrodynamic interaction results from the interaction of particles becomes more important [8]. The Hydrodynamic interaction consists of Acoustic Wake Effect and Mutual Radiation Pressure Interaction. The former is based on the asymmetric flow field around the particle moving in sound field and the latter is based on Bernoulli's principle. There are also some other mechanisms such as Acoustically Generated Turbulence, Acoustic Radiation Force, etc. which are generally considered unimportant compared with Orthokinetic interaction and Hydrodynamic interaction [9,10].

In this paper, Orthokinetic interaction and the situation that Re<1 are considered and Viscous force in Stokes region is chose as the main force here. The movements of particles with different sizes in both travelling field sound wave and standing field sound wave are calculated. The results under all kinds of frequencies, sound pressure level (SPL), initial phases, etc. are compared. These trials were carried out to study the motion of particles in sound wave field, which had great significance in studying acoustic agglomeration.

2. Theory: simulation model of particle motion in sound field

When a particle is travelling in sound wave field, its vibration will tend to lag behind the carrier medium. The degree of entrainment μ_p depends on many elements such as the size of the particle, the sound frequency and so on. The generalized equation of particle motion can be can be written as[11]

$$m_p \frac{du_p}{dt} = \delta m_p \frac{du_g}{dt} + \frac{1}{2}\delta m_p \frac{d(u_g - u_p)}{dt} + 6\pi\mu R(u_g - u_p) + 6R^2\sqrt{\pi\mu\rho_g}\int_{-\infty}^{t} \frac{d(u_g - u_p)}{d\eta}\cdot\frac{d\eta}{\sqrt{t-\eta}} \quad (1)$$

In Eq. (1), u_g and u_p stand for the velocity of the medium and the particle respectively. The left side of the equation is the resultant force acting on the particle. The first right-hand side term is pressure gradient force caused by the fluid in absence of particle. The second term describes the force required to accelerate the fluid in the direct vicinity of the particle. The next term is viscous Stokes' drag. The last term accounts for the history of the particle on the acceleration received in the preceding instants of time. Since the particle intensity is much bigger than the gas intensity ($\rho_p \gg \rho_g$), the first and the second terms can be neglected unless the gas pressure is very high. And based on the Stokes viscous force we considered here, the last term can also be neglected. Then we get the following equation by limiting the particle motion due to Stokes viscous force (Re<1):

$$F_p = 6\pi\mu R(u_g - u_p)\,. \quad (2)$$

Combine Eq.(2) with the wave equation of the medium:

$$u_g = u_0 \sin\omega t\,. \quad (3)$$

The solution has this form:

$$u_p = \frac{u_0 \sin(\omega t - \varphi)}{\sqrt{1+\omega^2 {\tau_d}^2}} + \frac{\omega \tau_d u_0 e^{-t/\tau_d}}{1+\omega^2 {\tau_d}^2}, \tag{4}$$

where ω is angular frequency, τ_d stands for the particle relaxation time which is described as

$$\tau_d = \frac{2\rho_p R^2}{9\mu}, \tag{5}$$

and φ is phase shift between the vibration of the gas medium and that of the particle, and μ is dynamic viscosity of gas medium. All particles are carried along with the medium, with a certain amount of retardation because of inertia. In Eq. (4), the second term of the right hand side is a transient term and it can be neglected since τ_d is much more less than the vibration period of the sound. Then the particle motion equation can be described as

$$u_p = \frac{1}{\sqrt{1+\omega^2 {\tau_d}^2}} u_0 \sin(\omega t - \varphi), \tag{6}$$

and the expression of the degree of entrainment μ_p in Stokes' Region can be defined as [12]

$$\mu_p = \frac{1}{\sqrt{1+\omega^2 {\tau_d}^2}} = \cos\varphi. \tag{7}$$

The vibration equation of gas medium in travelling wave sound field and standing wave sound field can be described respectively as

$$y_t(\mathrm{x,t}) = A\sin(\omega \mathrm{t} - \mathrm{kx}), \tag{8}$$

$$y_s(\mathrm{x,t}) = -2A\cos(\omega \mathrm{t})\sin(\mathrm{kx}). \tag{9}$$

According to Eq. (6) and Eq. (7), the vibration velocity of particles in travelling wave sound field and standing wave sound field can be calculated like this

$$u_{pt}(\mathrm{x,t}) = \mu_p \omega A\cos(\omega \mathrm{t} - \mathrm{kx} - \varphi), \tag{10}$$

$$u_{ps}(\mathrm{x,t}) = \mu_p 2\omega A\sin(\omega \mathrm{t} - \varphi)\sin(\mathrm{kx}), \tag{11}$$

and the expressions of particle displacement are

$$y_{pt}(\mathrm{x,t}) = \mu_p A\cos(\omega \mathrm{t} - \mathrm{kx} - \varphi), \tag{12}$$

$$y_{ps}(\mathrm{x,t}) = -2\mu_p A\cos(\omega \mathrm{t})\sin(\mathrm{kx}). \tag{13}$$

In these expressions, A stands for the vibration amplitude of gas medium and k is wave number. They can be expressed as

$$A = \frac{\sqrt{2} p_e}{\rho_0 c_0 \omega}, \tag{14}$$

$$k = \frac{2\pi f}{c_0}. \tag{15}$$

In Eq. (14) p_e is effective sound pressure which can be get from SPL given in calculation due to the following expression

$$SPL = 20\log\frac{p_e}{p_{ref}}, \tag{16}$$

here p_{ref} is reference sound pressure and it is generally count as 2×10^{-5}Pa.

In this paper, all the calculations were done under 20℃ and 1.013×10^5Pa. The sound velocity c_0 in this condition was about 344m/s. Particle density was counted as 2600kg/m^3 and the gas medium is air.

3. Results and discussion

3.1. The degree of entrainment

Fig. 1 shows that how sound frequency and particle size affect on the degree of entrainment μ_p. When particle gets larger, the frequency that can completely carry the particle becomes lower and for relatively smaller particles it gets easier to be carried completely by a larger range of frequencies, and particles bigger than 1mm can hardly be carried by sound with the frequency higher than 500Hz.

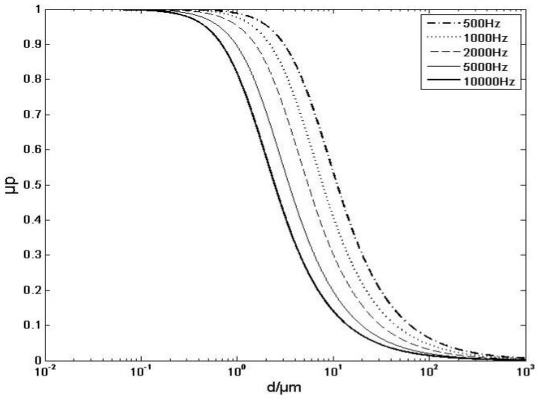

Fig. 1. The relationship between Particle entrainment factor μ_p and particle size for different frequencies

3.2. Particle movement in sound wave field

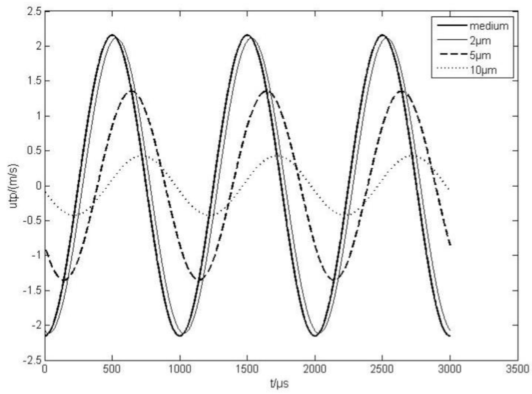

Fig. 2. Movements of particles with different sizes, f=1000Hz, SPL=150dB, x=0.5λ.

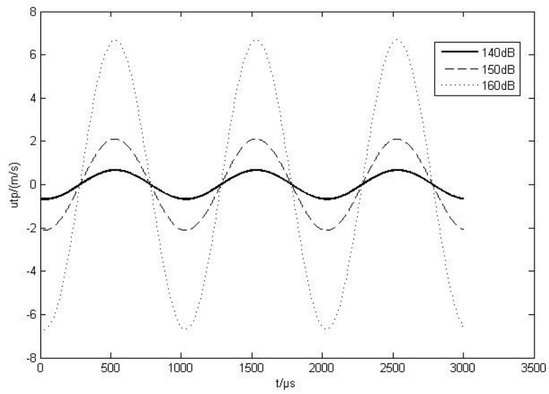

Fig. 3. Movements of particles under different SPL, f=1000Hz, d=2μm, x=0.5λ.

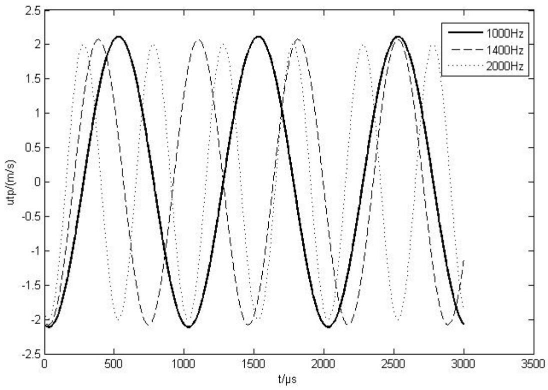

Fig. 4. Movements of particles under different frequencies, SPL=150dB, d=2μm, x=0.5λ.

Fig. 2 shows the movements of particles with different sizes. It's obviously that the bigger the particle is, the lower the particle vibration amplitude is. And there is a phase shift between the motion of the medium and particles which becomes bigger for lager particle diameter. Fig. 3 shows the effect of SPL. The peak velocity of the particle increases with the increase of SPL, and when it comes to 160dB, the peak velocity of 2μm particle can reach more 6m/s. The influence of frequency is shown in Fig. 4. In indicates that a higher frequency means a longer period, and for the same particle with a diameter of 2μm, the increase of the frequency makes the peak velocity of the particle decreases a little bit since entrainment factor is a little changed.

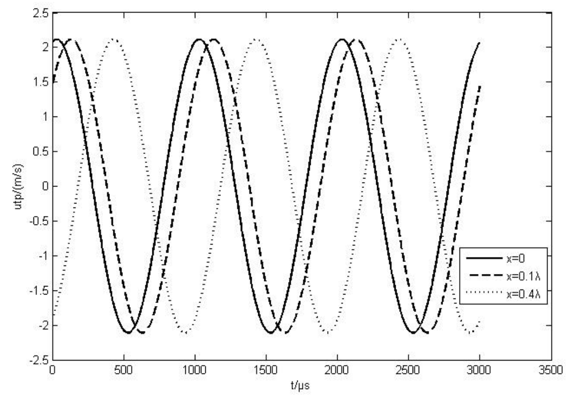

Fig. 5. Movements of particles at different initial places in travelling wave sound field, f=1000Hz, SPL=150dB, d=2μm.

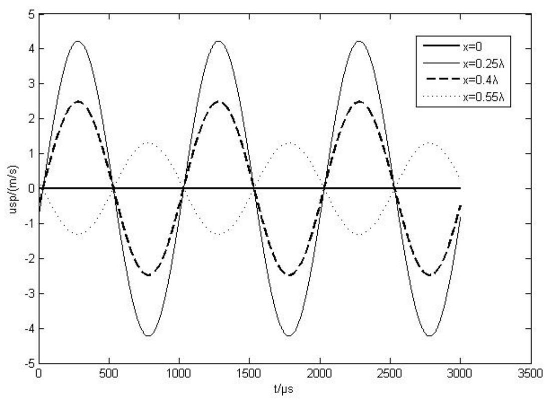

Fig. 6. Movements of particles at different initial places in standing wave sound field, f=1000Hz, SPL=150dB, d=2μm.

In Fig. 5 it is clear that in the same condition, the movement of particles at different initial places in a travelling wave sound field only have difference in initial phase. However, when particles are in a standing wave sound field, as shown in Fig. 6 there are wave nodes and antinodes. At the wave nodes particles don't vibrate at all and at the antinodes particles vibrate with the largest amplitude all the time. Particles will move towards to the wave nodes for a relatively stable state, which might be quite helpful for the agglomeration. But the real differences of travelling wave sound field and standing wave sound field in agglomeration is still not clearly studied yet.

4. Conclusion

In this paper, the movements of particles in both travelling wave sound field and standing wave sound field were calculated, and the influences of particle size, sound frequency, SPL and the initial place were considered. The results showed that particle size and frequency have great effect on the entrainment factor and a higher SPL caused larger vibration amplitude. The existences of wave nodes and antinodes made a standing wave sound field quite different from a travelling one.

In the future work, the process of acoustic agglomeration between two particles will be focused on and experiments on particle motion detecting in sound wave field will be carried out to verify the numerical result.

Acknowledgements

This work was supported by a grant from the Major State Basic Research Development Program of China (973 Program) (No. 2013CB228500) and the Program of Introducing Talents of Discipline to University (No. B08026).

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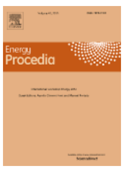

Biography

Prof. Zhongyang Luo, Director of CEU, Cheung Kong Scholar, Winner of National Funds for Talented Professionals. Research fields includes Clean coal combustion science and technology, Utilization of bio-energy and solar energy, Pollutants control during coal/biomass combustion and gasification, etc.